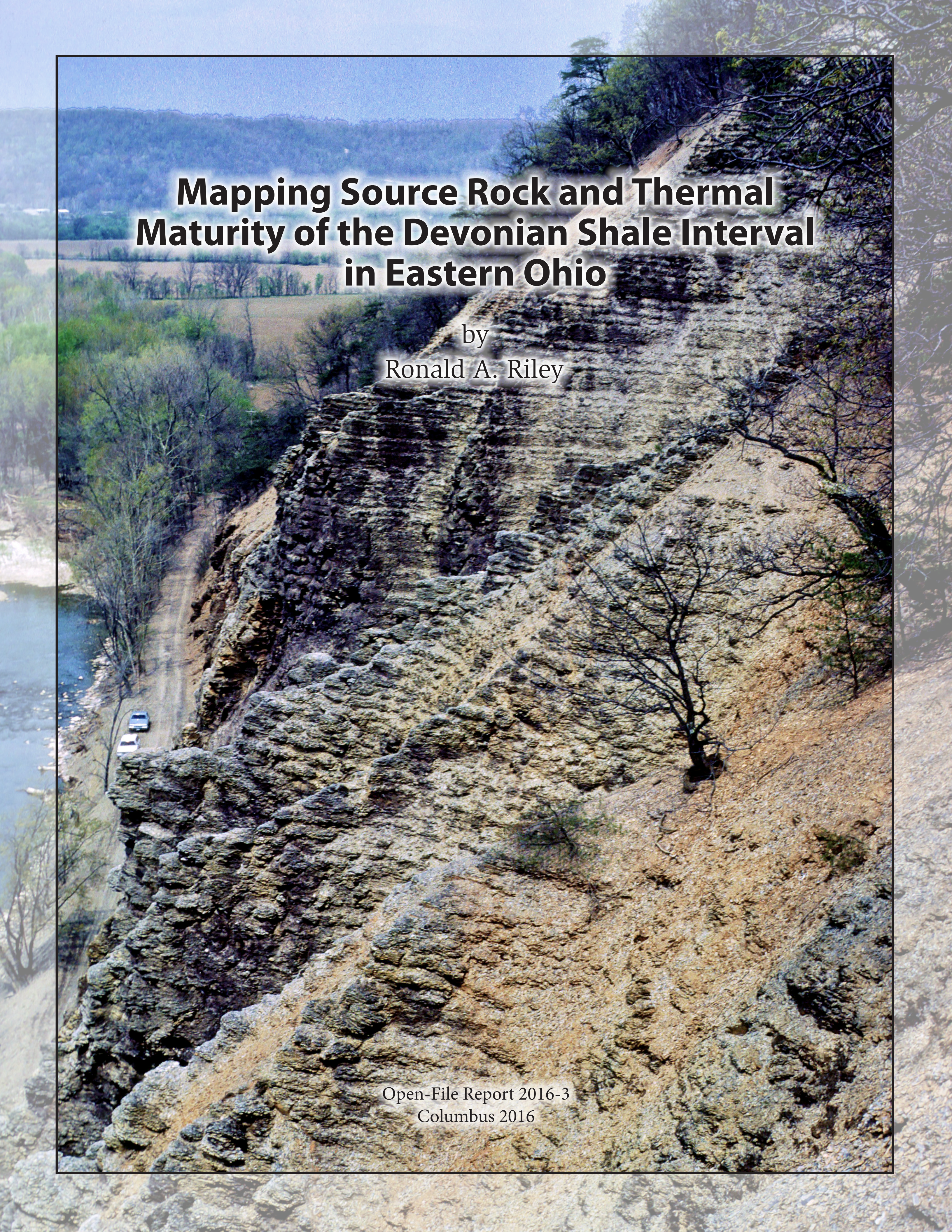
Mapping Source Rock and Thermal Maturity of the Devonian Shale Interval in Eastern Ohio



by

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Cover image: Ohio Shale exposure at Copperas Mountain in Ross County, Ohio.

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ABBREVIATIONS USED IN THIS REPORT

Units of Measure

Foot/feet .... ft
Gram(s) ....g
Kilometer(s) ....km
Meter(s) .... m
Mile(s) ....mi
Milligram(s) ....mg

Other

Eastern Gas Shales Project.................. EGSP
Gas Research Institute...........................GRI
Hydrocarbons.......................................HC
Total organic carbon ....TOC
U.S. Department of Energy ....DOE
U.S. Geological Survey .... USGS

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by Ronald A. Riley

ABSTRACT

The stratigraphic interval for this investigation extends from the top of the Middle Devonian Onondaga Limestone to the base of the Upper Devonian Berea Sandstone. Devonian shale source rock geochemistry and thermal maturity data were compiled from all available published sources and from archived data for 201 wells in eastern and central Ohio. From this comprehensive database, maps of total organic carbon (TOC), existing hydrocarbons (S_1), hydrocarbons generated during pyrolysis (S_2), vitrinite reflectance (%R_o), and conodont alteration index (CAI) were constructed to better refine the source rock generative potential and thermal maturity of the Devonian shale interval in eastern Ohio. Generally, westward increases in TOC, S_1, and S_2 were evident from these preliminary maps. Maximum TOC values per well ranged from 0.5 to 18.4 percent with over 70 percent of the wells having values greater than 4 percent, which is considered excellent source rock potential. The maximum value of TOC for the Devonian shale was over twice that of the Upper Ordovician Utica-Point Pleasant interval in eastern Ohio. The maximum S_1 value was 8.6 milligrams of hydrocarbons per gram (mg HC/g) of rock (excellent source rock generative potential) and generally ranged from 1 to 2 mg HC/g of rock (good source rock generative potential). Maximum S_2 values were often in the range of 10–20 (very good) or 20–40 (excellent) mg HC/g rock. Thermal maturity maps using %R_o and CAI revealed a basinward (eastward) transition to more thermally mature rocks. Maximum vitrinite reflectance values ranged from 0.33 to 1.34 %R_o. A 0.6 %R_o isograd trends northeast–southwest through eastern Ohio, marks the onset of oil generation, and separates the immature region to the west. The oil window transitions eastward to a condensate or wet gas window at values between 1.1 and 1.4 %R_o. "Vitrinite suppression" was indicated by both a comparison with %R_o of the overlying coals and with reported historic production. While current Devonian shale horizontal drilling is focused on the Marcellus Shale, these maps and data present strong evidence that other organic-rich Devonian shale units, such as the overlying Huron Shale Member and Rhinestreet Shale Member, also have significant oil and gas potential and may be good candidates for modern-day horizontal drilling techniques.

INTRODUCTION

The application of horizontal drilling combined with multistage hydraulic fracturing has resulted in a boom in drilling for unconventional gas and oil throughout the United States during the past decade. Since 2006, this technology has stimulated drilling activity and production from the Devonian Marcellus Shale in eastern Ohio and the Appalachian Basin and more recently, for other Devonian shale intervals such as the Rhinestreet Shale Member. The high potential for oil-and-gas production in these black, organic-rich shales has created an aggressive leasing-and-permitting program by many large independent and major oil companies in Ohio and the Appalachian Basin since the latter part of 2010.

With this renewed interest in shale exploration, additional Devonian black shale well cuttings and core archived at the Ohio Department of Natural Resources, Division of Geological Survey (Ohio Geological Survey) core repository have been sampled and analyzed by oil-and-gas operators since 2011. Recent public domain data is extremely important to define target areas for Devonian shale exploration and to assist in updating and refining the resource assessment of the Devonian black shale interval. The data compilation and mapping project described herein are a result of the Ohio Geological Survey efforts to provide one comprehensive database on Devonian shale source rock geochemistry and thermal maturity data to be used for evaluating and mapping the geographic limits of this important and prolific oil-and-gas play in eastern Ohio.

Various studies on Devonian shale thermal maturity have been published by the U.S. Geological Survey (USGS)from selected sample sets in Ohio and across the Appalachian Basin region. These investigations did not include archived data published in previous U.S. Department of Energy/Eastern Gas Shales Project (DOE/EGSP) and Gas Research Institute (GRI) studies during the 1970s and 1980s. In addition, source rock geochemistry and thermal maturity analyses on numerous Devonian shale cores and cuttings in storage at the Ohio Geological Survey core repository recently have become public domain data. When combined with published geochemical data from previous DOE/EGSP, GRI, and USGS studies, this recently acquired data has created a larger, more extensive data set to map and evaluate this regionally extensive Devonian shale unconventional target.

Source Rock Geochemistry Terms and Definitions

The following definitions and descriptions are provided to aid in better understanding of basic source rock potential properties as they are discussed in this report.

Total organic carbon (TOC) is a measurement in weight percent of the quantity of organic carbon preserved in a rock sample and includes both kerogen and bitumen (Peters and Cassa, 1994). Organic content is largely controlled during sedimentation by biologic productivity, sediment mineralogy, and oxygenation of the water column and sediment. The TOC is a useful qualitative measure of petroleum potential. A TOC of 0.5 percent generally is regarded as the minimum for defining a petroleum source rock, but most geochemists consider a TOC of greater than 1.0 percent as a good source rock for generating petroleum potential (table 1).

Kerogen is the portion of organic carbon particulate matter that is insoluble and remains after extraction of organic solvents. It is derived from the breakdown of both marine and land-derived plant and animal matter.

Bitumen is the portion of organic matter that is soluble in organic solvents. It is generally derived from the cracking (thermal disassociation) of the kerogen and to a lesser extent from lipid compounds from once-living organisms. In a broader, informal sense it refers to tar, pitch, and asphalt.

Rock-Eval pyrolysis parameters and definitions

S_1 values are a measurement (mg HC/g of rock) of the free hydrocarbons already generated that are volatilized out of the rock without cracking the kerogen. The hydrocarbons are distilled out of the rock sample at initial heating to a temperature of 350°C. These values may be anomalously high from migration and contamination by drilling fluids and mud. An S_1 of greater than 1 is considered to be a good source rock (table 1).

S_2 is a measurement (mg HC/g of rock) of the amount of hydrocarbons generated through thermal cracking of kerogen and heavy hydrocarbons. It represents the existing potential of a rock to generate hydrocarbons and is a more realistic measure of source rock potential than TOC, which includes "dead carbon" incapable of generating hydrocarbons. The S_2 generally decreases with burial depths greater than 1 km. A S_2 of greater than 5 is considered to have good source rock generative potential (table 1).

Thermal maturity measurements and definitions

Vitrinite reflectance (%R_o) and conodont alteration index (CAI) are two of the primary indicators used to assess the thermal maturity of source rocks, and both were mapped for this project. Other evaluation methods for assessing thermal maturity include the hydrogen index (HI) and the production index (PI); both are derived from Rock-Eval pyrolysis measurements (Wallace and Roen, 1989; Peters and Cassa, 1994; McCarthy and others, 2011). The temperature (°C) of maximum release of hydrocarbons (T_{max}) is another Rock-Eval measurement used for determination of thermal maturity and is sometimes used in deeper, pre-Carboniferous geologic units where vitrinite is absent (Wallace and Roen, 1989; Peters and Cassa, 1994). Ryder and others (2013) provide a detailed discussion of multiple parameters used for determining thermal maturity of Devonian shales in the northern Appalachian Basin, including %R_o, gas chromatography (GC) spectra of bitumen extracts, organic matter type, spectral fluorescence of *Tasminites* algae, and HI values.

Vitrinite reflectance (%R_o) is a key diagnostic tool for assessing thermal maturity and is based on measuring the reflectivity (R) of vitrinite through

TABLE 1. ***Measured geochemical parameters describing source rock generative potential from TOC, S_1, S_2, and $S_1 + S_2$***[†]

Quality	TOC wt. %	S_1 mg HC/g rock	S_2 mg HC/g rock	$S_1 + S_2$ mg HC/g rock
Poor	<0.5	0–0.5	0–2.5	0–3.0
Fair	0.5–1.0	0.5–1.0	2.5–5.0	3.0–6.0
Good	1.0–2.0	1.0–2.0	5.0–10.0	6.0–12.0
Very good	2.0–4.0	2.0–4.0	10.0–20.0	12.0–24.0
Excellent	>4.0	>4.0	>20.0	>24.0

[†]Modified from Peters (1986) and Wallace and Roen (1989).

a microscope equipped with an oil-immersion objective lens and photometer. Vitrinite is a maceral (plant and animal remains) found in many kerogens and is formed from the thermal alteration of lignin and cellulose in plant walls. As temperature increases, vitrinite undergoes complex, irreversible aromatization reactions that increase the reflectance. Reflectance measurements represent the percent of light reflected in oil, designated as $\%R_o$. The oil window generally falls within a $\%R_o$ ranging from 0.6 to 1.4 (table 2). Values less than 0.6 $\%R_o$ are considered immature and those over 1.4 $\%R_o$ are considered overmature.

Conodont alteration index (CAI) is based on color changes seen in microscopic-sized fossil teeth from the remains of eel-shaped chordates. These fossils are highly resistant to weathering and metamorphic temperature regimes and contain trace amounts of organic matter. Their color alteration is time and temperature dependent and is a progressive, irreversible condition, making them ideal for correlating to maximum temperatures. The CAI can be determined by comparing samples against a set of conodont color standards (table 2). Using CAI thermal maturation indices, the oil and gas windows are in a gradational boundary. The onset of oil generation is placed between 1.0 and 1.5, and the limit of oil generation is between 2.0 and 2.5 (Harris, 1979).

TABLE 2. ***Thermal maturity parameters describing types of hydrocarbon generated from Tmax, P_I, $\%R_o$, and CAI***†

Type	T_{max} (°C)	PI [$S_1/(S_1+S_2)$]	$\%R_o$	CAI
Immature	<435	<0.1	0.2–0.6	0–1.0
Top oil window	435–445	0.1	0.6	1.0–1.5
Bottom oil window	470	0.4	1.4	1.5–2.0
Postmature	>470	>0.4	>1.4	>2.0

†Modified from Peters and Cassa (1984).

PREVIOUS WORK

Previous work on the source rock properties and thermal maturity of the Devonian shale interval in Ohio and the Appalachian Basin have been published in studies funded by the DOE/EGSP and the GRI and also from reports published by the USGS. These reports and associated data provide a wealth of historical data from which to reexamine the Devonian shale resources in Ohio and surrounding Appalachian Basin states.

Reports published by EGSP contained data sets for 12 Devonian shale cores from eastern Ohio analyzed by Geochem Research, Inc. (U.S. DOE, 2007). These geochemical data reports included total organic carbon (TOC) and vitrinite reflectance ($\%R_o$) measurements, as well as density measurements, visual kerogen assessments, saturated hydrocarbon analyses, biostratigraphic identification, and mineralogical analyses throughout the entire Devonian shale interval.

Investigations funded by GRI included source rock geochemistry data from 98 Devonian shale sidewall core plugs from 4 wells in southeastern Ohio (Owen and others, 1985). This joint study by Terra Tek, Inc., Stocker and Sitler, and ResTech, Inc., contained TOC, Rock-Eval pyrolysis, and measured vitrinite reflectance data. ExLog/Brown and Ruth (1988) also published Devonian shale geochemical data based on cores and well cuttings from 18 wells in eastern Ohio. In another GRI-sponsored project, 98 full-diameter Devonian shale cores were taken along the outcrop trend in the early 1980s. This cooperative project between the Institute of Gas Technology (IGT), HYCRUDE Corporation, Phillips Petroleum Company, and Bechtel Group sought to determine the feasibility of hydroretorting organic-rich shale for oil recovery (Weil and others, 1978). Although never commercially performed in Ohio, the Hytort process, developed by HYCRUDE Corporation, used hydrogen-rich gas during retorting to enhance oil yields from oil shales. Archived data for these 98 cores included TOC measurements, wireline logs, core descriptions, and calculated oil yield in gallons per ton. These cores and data permanently reside at the offices of the Ohio Geological Survey.

U.S. Geological Survey Devonian shale investigations included Milici and Swezey (2006), Rowan (2006), Repetski and others (2008), East and others (2012), Ryder and others (2013), Hackley and others (2013), and Repetski and others (2014). Rowan (2006) examined the burial and thermal history of the central Appalachian Basin using 2-D models for the Cambrian through Permian interval. In a resource assessment of the Devonian shale in the Appalachian Basin, Milici and Swezey (2006) used vitrinite reflectance ($\%R_o$) to assist in their evaluation. Milici and Swezey (2006) noted that $\%R_o$ values appeared to be underestimated based on a comparison to the $\%R_o$ values of the overlying Pennsylvanian coal beds; this phenomenon was described as “vitrinite reflectance suppression.” Repetski and others (2008) mapped thermal maturity patterns for Ordovician and Devonian rocks in the Appalachian Basin using both CAI and $\%R_o$. East and others (2012) constructed a regional thermal maturity map of the Devonian shale based on $\%R_o$ that included the Illinois, Michigan, and Appalachian Basins. Thermal maturity of the Devonian shale in the northern Appalachian Basin was examined by Hackley and others (2013) using multiple techniques. Vitrinite reflectance, Rock-Eval pyrolysis, gas chromatography, and GC-mass spectrometry were evaluated on three transects. Results from vitrinite reflectance indicated that most samples in eastern Ohio were immature, and higher vitrinite reflectance values were present in the overlying Pennsylvanian coals; these findings supported previous studies that vitrinite reflectance values in the Devonian shale appeared to be suppressed. A major revision of thermal maturity patterns was made by Repetski and others (2014) for Devonian and Ordovician rocks in the Appalachian Basin using CAI and vitrinite reflectance data. In their study, the distribution of Devonian CAI and $\%R_o$ were related to structural features and oil-and-gas fields.

METHODOLOGY

For this project, Devonian shale source rock geochemistry and thermal maturity data were compiled from published sources and from all archived data on file at the Ohio Geological Survey. Archived data included older source rock data from Devonian shale research dating back to the 1970s and 1980s along with recently submitted data (since 2011) for unconventional shale exploration using horizontal drilling and massive hydraulic fracturing. Published sources included reports and data from the USGS, the EGSP studies, and GRI investigations. The USGS has sampled numerous cores and cuttings from the Devonian shale interval over the past decade.

Published references on source rock geochemistry for the Devonian shale interval were compiled and all pertinent source rock data from these publications were entered into a digital database that was incorporated into the geochemistry source rock and thermal maturity mapping. All historic and recent source rock geochemistry data submitted to the Ohio Geological Survey was entered into a digital database. The data was edited for accuracy and completeness. The Ohio Geological Survey source rock geochemistry database represents all public domain data and includes older data from the 1970s and 1980s, as well as recent data obtained from operators. Source rock data compiled and used for this investigation are listed in the Appendix, and the well locations are shown in Figure 1.

For this investigation, source rock geochemistry data was available for 201 unique wells in the study area of eastern Ohio (fig. 1). For some wells, geochemical analyses were performed on the same well by multiple operators. Of the 201 unique wells, 175 wells had TOC data, 118 wells had S_1 and S_2 data, and 55 wells had $\%R_o$ data. Published CAI data was available for only 17 wells in the mapped area, with 13 in Ohio and 4 in West Virginia for additional control. Samples for additional CAI analyses for the Devonian Onondaga Limestone interval were collected from 13

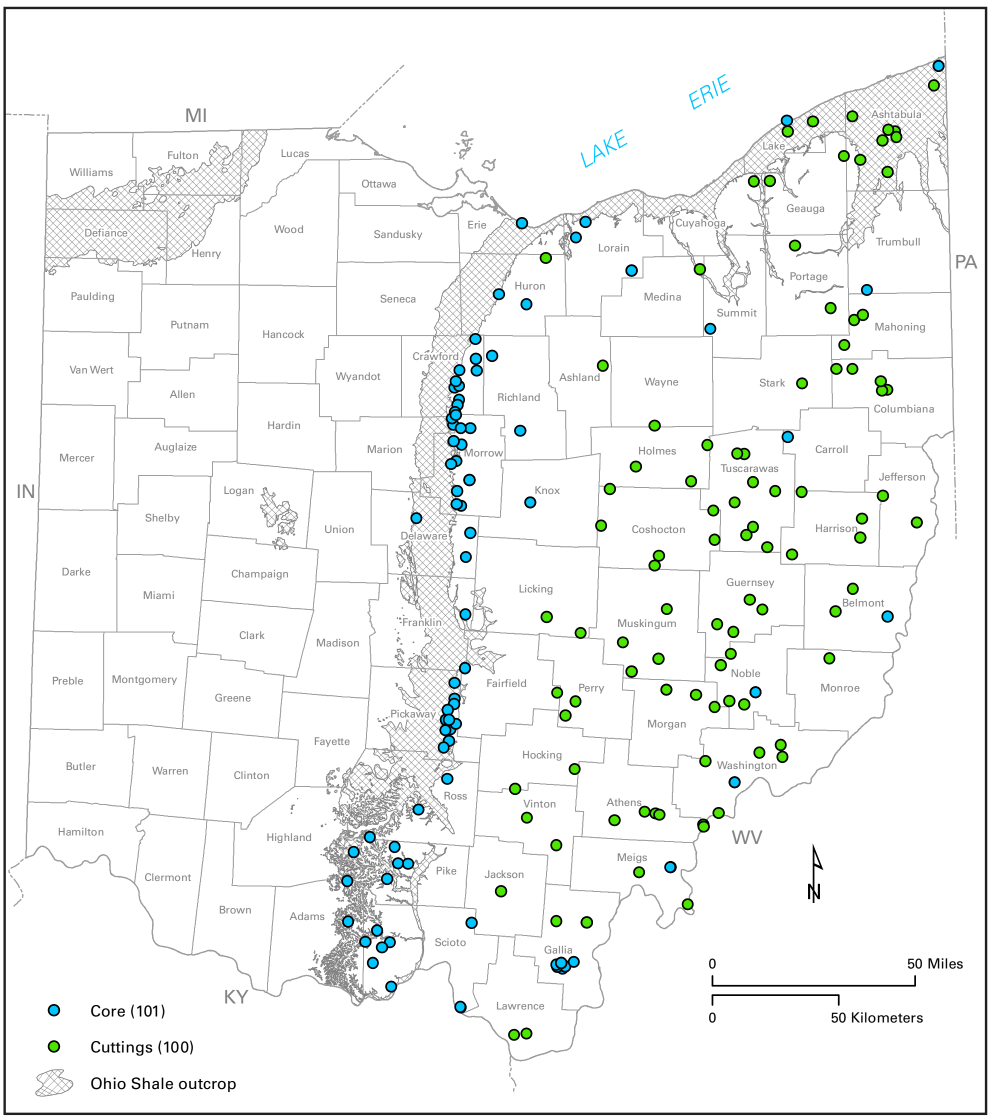

FIGURE 1. Sampled wells used for source rock mapping of the Devonian shale interval in eastern Ohio.

additional wells in eastern Ohio to provide a better geographic distribution of data. These samples were sent to the USGS to determine the CAI, but results were unavailable by the publication of this report.

The source rock data was reviewed for accuracy. Data reported as suspect by the laboratory analyses company were removed to improve the accuracy of the interpretation and mapping. For $\%R_o$ measurements, only those samples identified as indigenous were used for mapping. Other measured values from cuttings that were not indigenous were considered suspect and may have been from caving material from higher stratigraphic intervals. Queries were performed to calculate the average and maximum values of the Devonian shale interval for the following attributes: TOC, S_1, S_2, $\%R_o$, and CAI.

Preliminary maps of TOC, S_1, S_2, $\%R_o$, and CAI per well were constructed using IHS Petra® software. The final maps for this report were generated using ESRI ArcGIS® software for all mapped attributes. Each contour shape file was manually edited to honor all data points. Anomalous data values were examined from the original data sources, and the database was edited where data was suspect. For consistency, the maximum values of source rock attributes were mapped for this project. It should be noted that data was sampled from both core and well cuttings, which may skew the data. Sampling from core is generally more selective since the more organic-rich zones are targeted for analyses. Sampling from well cuttings are blended or mixed over a 10 to 20-ft (3–7-m) interval. Thus measured values for well cuttings may be suppressed when compared with those sampled from cores.

REGIONAL STRATIGRAPHIC AND STRUCTURAL SETTING

The Devonian shale sequence of eastern Ohio is an eastward-thickening wedge of sediments on the western flank of the Appalachian Basin. This eastward-thickening stratigraphic interval is well documented and illustrated in eastern Ohio and across the Appalachian Basin through numerous cross sections and schematic diagrams by various authors (Rich, 1951; Gray and others, 1982; Potter and others, 1982; Ohio Division of Geological Survey, 1988; Roen and Kepferle, 1993; Boswell, 1996; and Baranoski and Riley, 2013). These studies provided a subsurface stratigraphic framework that was tied into the Devonian shale outcrops in western New York and central and northeastern Ohio.

The Devonian shale stratigraphic interval for this investigation extends from the top of the Middle Devonian Onondaga Limestone to the base of the Upper Devonian Berea Sandstone (fig. 2 and plate 1). Stratigraphic nomenclature used for this investigation (fig. 2) is based on the nomenclature established for the EGSP (Gray and others, 1982) and also used in the GRI-Devonian shale study (Ohio Division of Geological Survey, 1988).

The basinwide Devonian shale sequence consists of two dominant facies: black, organic-rich shale and gray to greenish-gray, silty shale. The organic-rich shale units can be correlated regionally across the basin with wireline logs based on the higher gamma ray signature and typically higher porosity response on the density curve. The more organic-rich facies of the Marcellus Shale, Rhinestreet Shale Member of the Olentangy Shale, and Huron Shale Member of the Ohio Shale have been the primary targets for hydrocarbon production and exploration in this interval. In these unconventional reservoirs, the organic-rich shale serves as the source rock, reservoir, and seal. The Marcellus Shale has been extensively drilled with horizontal wells in western Pennsylvania, western West Virginia, and extreme eastern Ohio where thickness is greater than 50 ft (15 m). In Ohio, the Marcellus Shale reaches a maximum thickness of approximately 75 ft (23 m) in eastern Monroe and Washington Counties (Erenpreiss and others, 2011). The Marcellus Shale and Rhinestreet Shale thin westward and disappear in eastern Ohio, while the Huron Shale can be traced as far

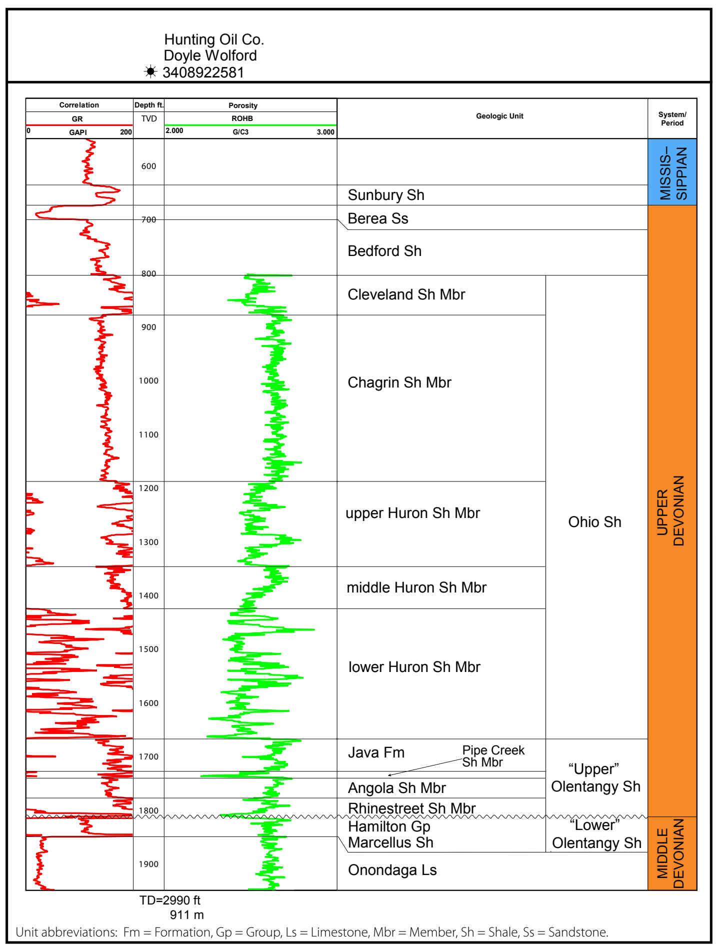

FIGURE 2. Typical well log from Licking County, Ohio, showing stratigraphic nomenclature for the Devonian shale interval in eastern Ohio.

west as the outcrop belt in central Ohio (plate 1). The Devonian shale outcrops at the surface in central Ohio trending north–south and then curves eastward along Lake Erie in northern Ohio. In the Appalachian Basin portion of Ohio, the Devonian shale interval is absent west of the outcrop belt with the exception of the Bellefontaine Outlier in Logn County. The Devonian shale interval thickens eastward to over 3,500 ft (1,067 m) in extreme eastern Ohio (fig. 3). The Devonian Antrim Shale (Ohio Shale equivalent) outcrops in northwestern Ohio at the southeastern edge of the Michigan Basin and deepens basinward to the northwest.

Devonian shales are thought to be transgressive basin-fill sequences related to active subsidence and tectonism (Potter and others, 1981). Deposition of these shales occurred in a shallow to deep foreland basin setting west of the active Acadian orogenic belt. Rapid transgression following the Middle Devonian unconformity resulted in sediment covering the Cincinnati and Findlay Arches. Controls on distribution and preservation of organic matter remains in debate, but the organics are thought to have been deposited during anoxic to dysoxic conditions (Potter and others, 1981). Black shales accumulated under low-energy conditions in a euxinic basin across the region far from the Acadian orogenic belt. These black shales are deeper-water facies equivalent to the clastics deposited from the Catskill delta to the east.

The top of the Devonian shale interval deepens basinward from the outcrop belt in central Ohio to more than 1,250 ft (380 m) below sea level in extreme eastern Ohio (fig. 4). Regional dip on the top of the Devonian shale interval averages about 30 ft per mi (5.7 m per km), but this may vary by local structural anomalies. The most prominent structural feature is the northwest–southeast-trending Cambridge Cross-Strike Structural Discontinuity. Three major fault zones are evident at the top of the Devonian shale interval and are named the Highlandtown Fault, the Akron-Suffield Fault System, and the Middleburg Fault.

DISCUSSION

Source rock geochemistry provides the fundamental information needed to evaluate and map the organic richness, type, and thermal maturity of a source rock. The resulting maps are a necessary step to aid in determining the stratigraphic and geographic extent of source rocks in the Devonian shale petroleum system. The volume, organic richness, and thermal maturity of these source rocks determine the amount of oil and gas that may be generated and become available for traps.

Source Rock Geochemistry

The preliminary findings of source rock geochemistry data for Ohio represent a first-round screening of Devonian black shale source rock potential based on recent and historical data. These data and interpretations do not take into account the sample quality. Rock sample quality for source rock measurements generally decrease in the following order: conventional full-diameter core, sidewall core, drill cuttings, and outcrops. Well cuttings may be contaminated by caving material from higher in the stratigraphic section or from drilling mud. Age of the rock samples also affects their reliability and source rock measurements. Samples that have been stored for long periods of time generally are reliable if they are cleaned and stored under proper conditions to restrict the growth of fungus (Peters and Cassa, 1994). For this project, data that was indicated to be suspect by the analytical laboratory was removed for mapping and interpretation purposes. Additional work is necessary to take into account the quality and storage time of rock samples used for these source rock measurements.

Source rock potential maps

Parameters to assess source rock generative potential for hydrocarbon production include TOC, S_1, and S_2. Source rock quality based on these parameters was defined by Peters (1986; table 1). Maximum TOC values for the Devonian shale interval in Ohio range from 0.5 to 18.4 percent in eastern and central Ohio (table A-1). Over 70 percent of the maximum TOC values per well were greater than 4 percent (excellent source rock generative potential). The maximum TOC map indicated a general westward increase in values across the state (fig. 5). Extreme eastern Ohio typically had values ranging from 2 to 4 percent, which is considered very good source rock generative potential. West of the 4 percent contour, maximum TOC was generally greater than 4 percent. The highest values were in central Ohio along the Devonian shale outcrop trend where maximum TOC values generally were greater than 10 percent. All values along the outcrop trend were taken from core samples. As noted previously, source rock measurements from core often exceed those from well cuttings because they generally are sampled preferentially in intervals of more organic-rich zones when compared with well cuttings, where the samples are blended over a 10 to 20-ft (3–7-m) interval. When compared with maps and data for the Upper Ordovician shale interval (Utica-Point Pleasant units) published by the Ohio Division of Geological Survey (2013a), the Devonian shale interval has significantly higher TOC values than the deeper Ordovician shales. Maximum TOC values for the Upper Ordovician shale interval typically ranged from 2 to 3 percent with a maximum value of 7.3 percent.

The S_1 and S_2 measurements also can be useful indicators of source rock potential (Peters, 1986; Wallace and Roen, 1989). Maximum S_1 values range from 0.2 to 8.6 mg HC/g of rock in Ohio (table A-1). A westward-increasing trend of higher S_1 measurements, similar to the TOC trend, is reflected on the S_1 isopleth map (fig. 6). Extreme eastern Ohio is generally in the 1 to 2 mg HC/g range, which is

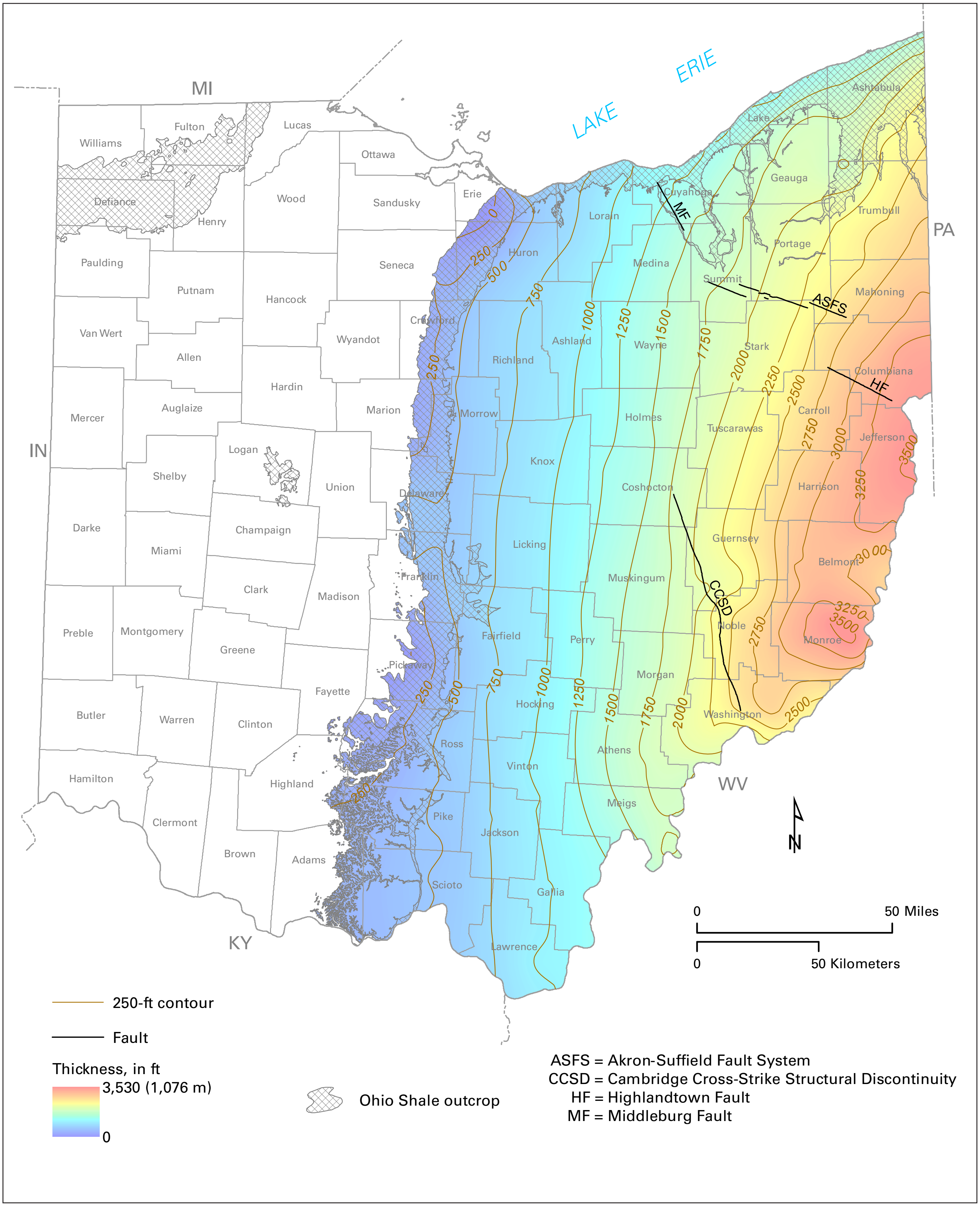

FIGURE 3. Map of interval thickness of the Devonian shale interval in eastern Ohio. Modified from Wickstrom and others (2005).

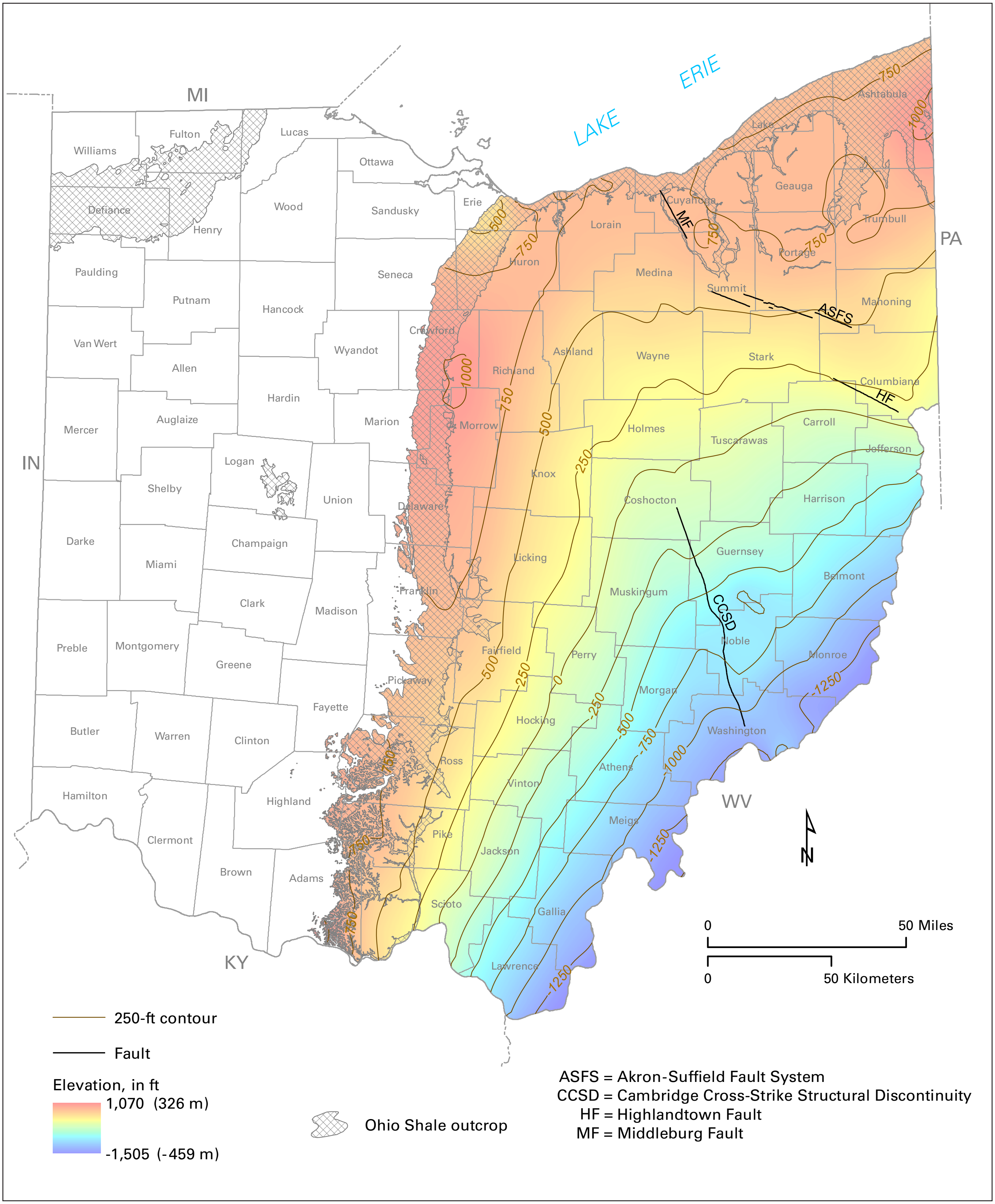

FIGURE 4. Structure map on top of the Devonian shale interval in eastern Ohio. Modified from Wickstrom and others (2005).

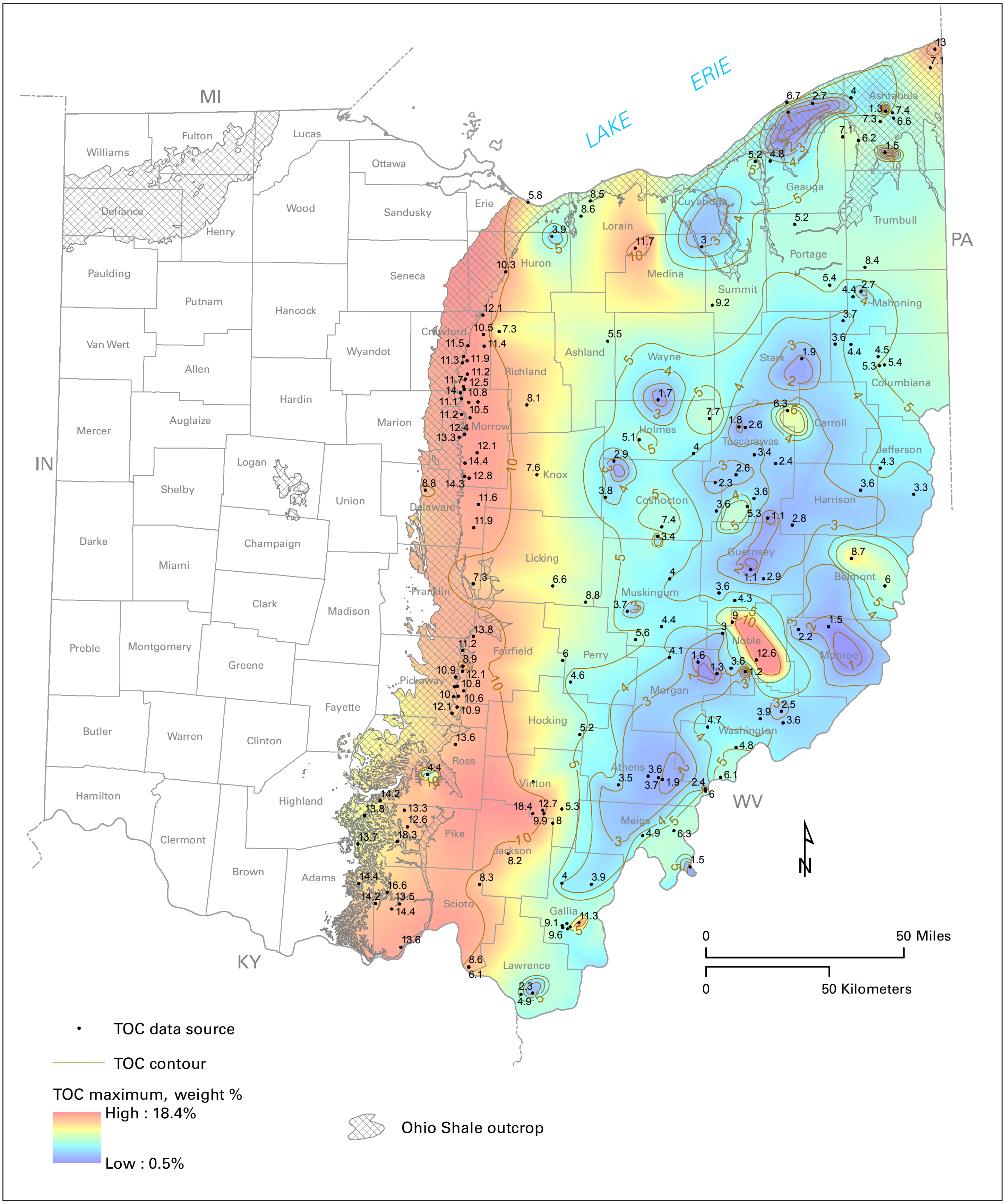

FIGURE 5. Isopleth map of the maximum total organic carbon (TOC) for the Devonian shale interval in eastern Ohio.

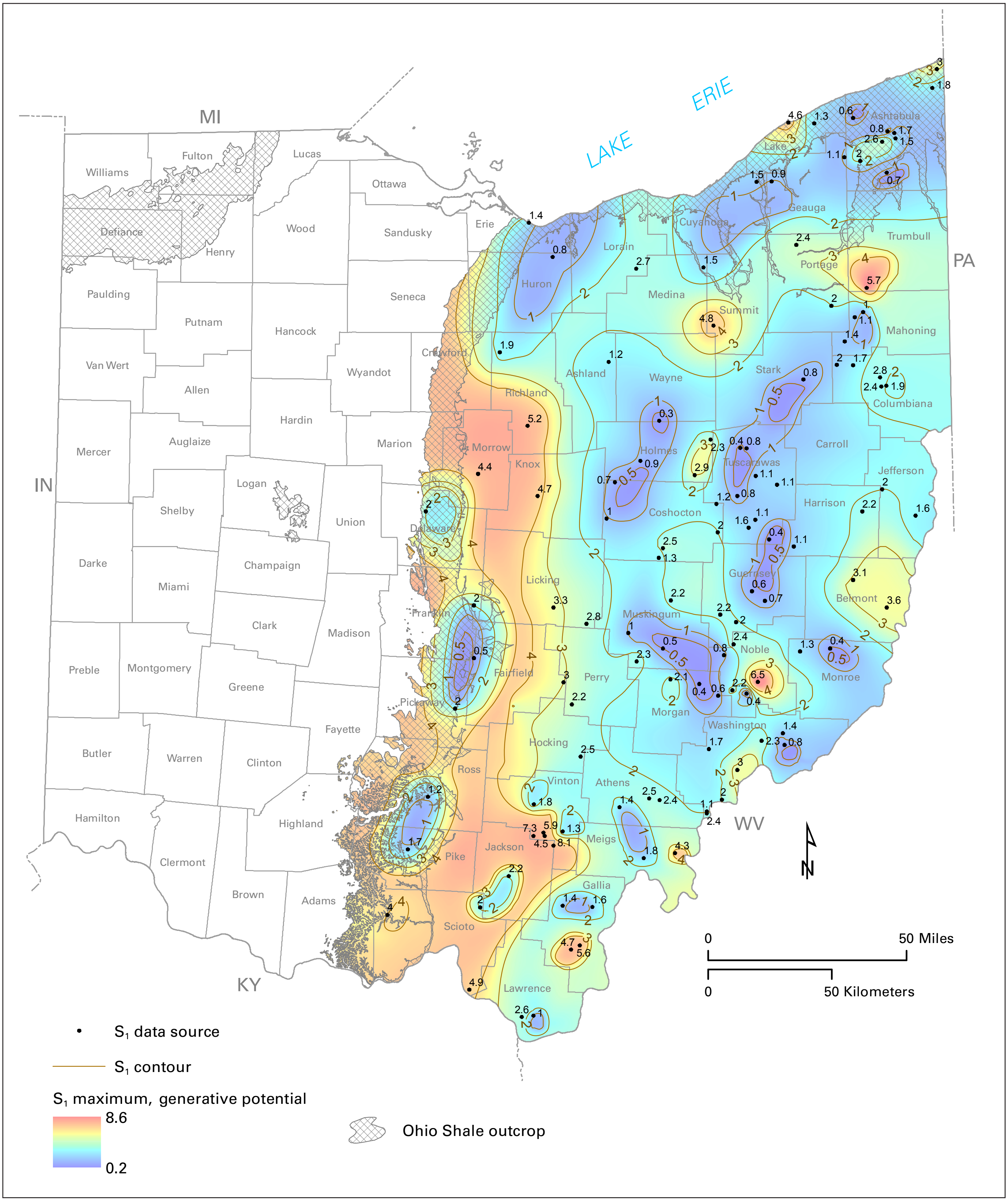

FIGURE 6. Isopleth map of the maximum S_1 (existing hydrocarbons) for the Devonian shale interval in eastern Ohio.

considered to be good source rock generation potential (table A-1). Measurements of S_1 and S_2 were not taken for the cores along the Devonian shale outcrop trend. Thus the majority of measurements for these maps are from well cuttings. The S_2 measurements for the Devonian shale interval range from 0.5 to 115 mg HC/g of rock in Ohio (table A-1). Extreme eastern Ohio contains S_2 values of less than 5 mg HC/g of rock (fair source rock generative potential). Most values are in the 10–20 (very good source rock generative potential) or 20–40 mg HC/g of rock range (excellent source rock generative potential). The S_2 map reflects a similar westward-increasing trend with the TOC and S_1 maps (fig. 7).

Thermal maturity maps

Maximum vitrinite reflectance values for the Devonian shale interval in Ohio ranged from 0.33 to 1.34 %R_o (table A-1). A basinward (eastward) transition to more thermally mature rocks is evident on the %R_o isograds (fig. 8). An immature region is evident throughout central and western Ohio where values trending northeast–southwest are less than 0.6 %R_o. Four local anomalies are present west of the 0.6 %R_o isograd where values exceed the 0.6 cutoff. These anomalies may be a result of false measurements from well cuttings that were not indigenous to the zone of interest. The onset of oil generation is considered to begin at 0.6 and to end at 1.1 %R_o (table 2). This narrow zone is present on the isograd map of the maximum vitrinite reflectance and trends northeast–southwest through eastern Ohio (fig. 8). The oil window transitions eastward to a condensate or wet gas window based on a thermal maturity of 1.1 to 1.4 %R_o (fig. 8). Using a cutoff of 1.4 %R_o, a dry gas window is not evident in the mapped area of Ohio but is shown to the east on regional maps of extreme western Pennsylvania and West Virginia by Ryder and others (2013) and Repetski and others (2014). As expected, %R_o values were lower than those on the deeper Upper Ordovician %R_o map (Ohio Division of Geological Survey, 2013b), but displayed the same eastward-maturing trend.

The phenomenon described by Lo (1993) as "vitrinite reflectance suppression" or underestimation of %R_o values has been recognized by numerous authors for the Devonian shale interval in the northern Appalachian Basin (Milici and Swezey, 2006; Hackley and others, 2013; Ryder and others, 2013; Repetski and others. 2014). Evidence for Devonian shale "vitrinite suppression" is supported by comparison to values in the overlying Pennsylvanian coals and the position of Devonian shale natural gas fields compared with mapped %R_o values in eastern Ohio.

Devonian shale %R_o values commonly are lower than those for the overlying coals that are 1,500 to 2,000 ft (450-600m)shallower. The %$R_{o(max)}$ of 0.6 for the Pennsylvanian isograd is up to 50 mi (80km) west of the 0.5 %R_o isograd for the Devonian shale interval (Ryder and others, 2013). Assuming the Pennsylvanian coal vitrinite measurements are accurate, this creates an inverted thermal maturity profile and indicates that the Devonian shale %R_o values are anomalously low. Explanations for this "vitrinite suppression" are related to syndepositional and post-burial processes that include bitumen impregnation, host rock lithology, overpressure, variations in vitrinite precursor material, and incorporation of organic sulfur (Hutton and Cook, 1980; Price and Barker, 1985; McTavish, 1998; Carr, 2000; Barker and others, 2007; Ryder and others, 2013).

The production of dry gas and absence of produced liquids from the Devonian shale in southeastern Ohio also indicates a thermal maturity greater than that indicated by the %R_o map. Devonian shale producing fields in southeastern Ohio are dominated by dry gas production with no oil reported (Riley and others, 2004). The vitrinite reflectance map shows values ranging from 0.6 to 1.0 %R_o (oil window) in these dry gas producing fields. These production numbers are further evidence that the vitrinite reflectance values may be suppressed. If these thermal maturity measurements are accurate, then natural gas likely migrated from the deeper part of the basin to the east.

All data for the CAI map was based upon a published report by Repetski and others (2008), and since no additional data was available for this project, the CAI map closely resembles that from their published study. The immature, oil, gas-and-oil, and gas windows are evident from this mapped data and also show an increased maturity basinward (fig. 9). The immature boundary (using a CAI value of 1 or less) that trends roughly north–south through central Ohio is influenced by a lack of data in western Ohio. The onset of oil generation is generally considered to begin at a CAI value of 1.0 and end at 2.0. Additional data points in eastern Ohio currently are being analyzed for CAI measurements but were not available for this publication.

CONCLUSIONS

During the past decade, exploration in the Devonian organic-rich black shale interval using horizontal drilling and massive hydraulic fracturing has generated additional source rock geochemistry data for this prolific, unconventional oil-and-gas play in Ohio, Pennsylvania, and West Virginia. Up to now, the focus of this drilling and exploration has been in the Marcellus Shale, the basal unit of the Devonian shale sequence. Based on historic conventional production and source rock geochemistry compiled for this project, other Devonian organic-rich shale units, such as the lower Huron Shale Member and Rhinestreet Shale Member, also have significant potential and are good candidates for modern-day horizontal drilling techniques.

Devonian shale source rock geochemistry and thermal maturity data was compiled from a detailed inventory of all published and archived sources to provide a

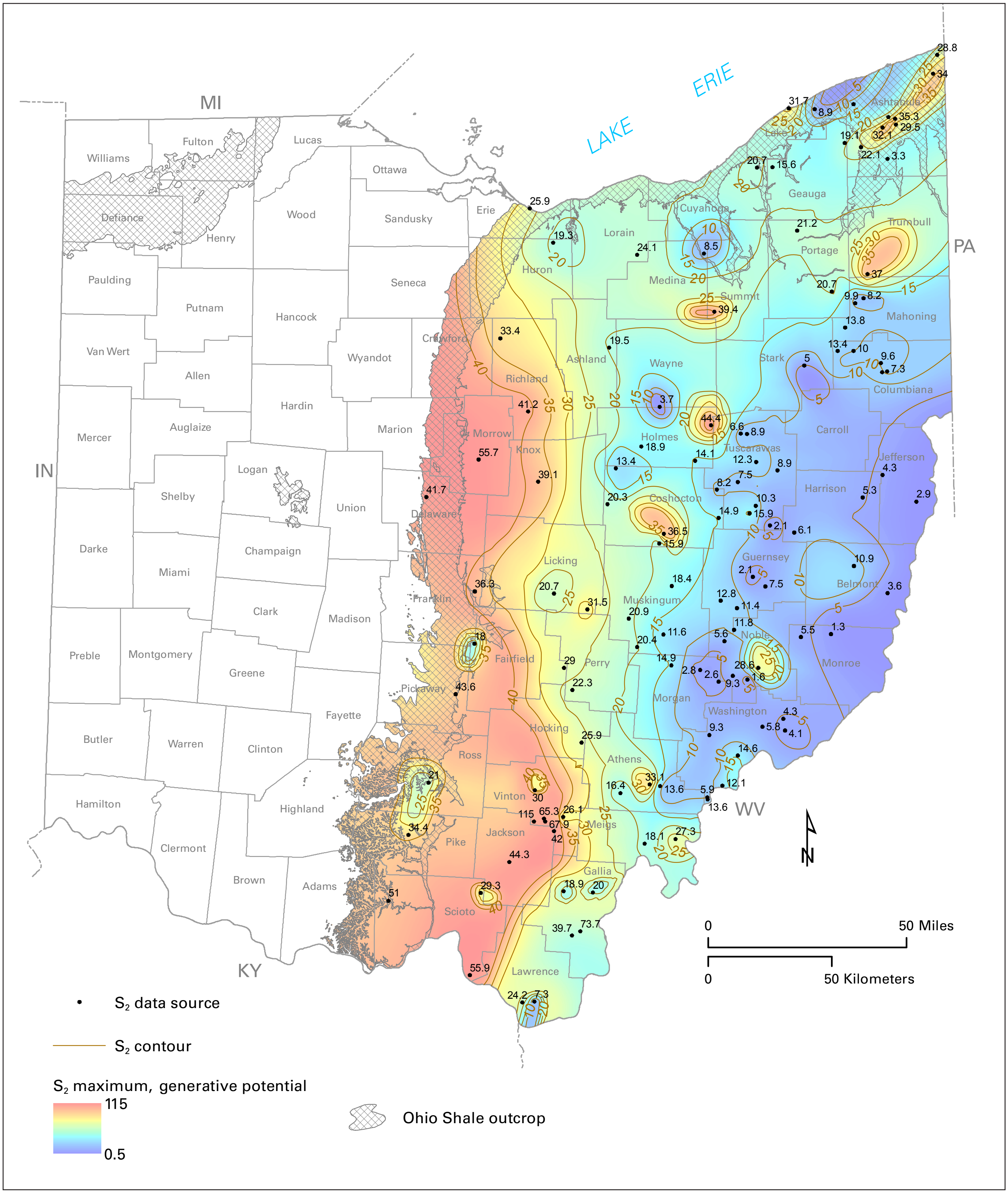

FIGURE 7. Isopleth map of the maximum S_2 (hydrocarbons generated during pyrolysis) for the Devonian shale interval in eastern Ohio.

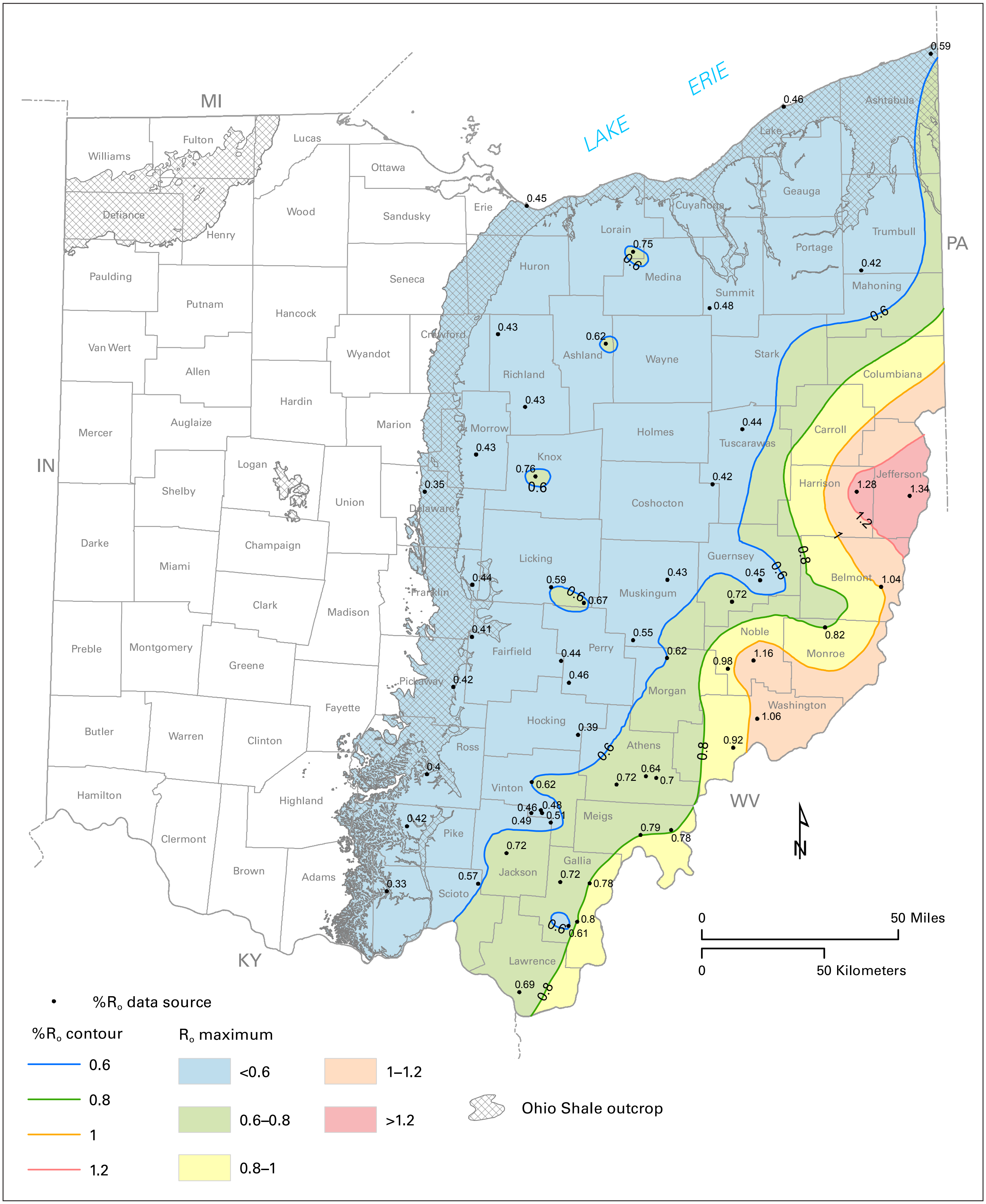

FIGURE 8. Isograd map of the maximum vitrinite reflectance (%R$_o$) for the Devonian shale interval in eastern Ohio.

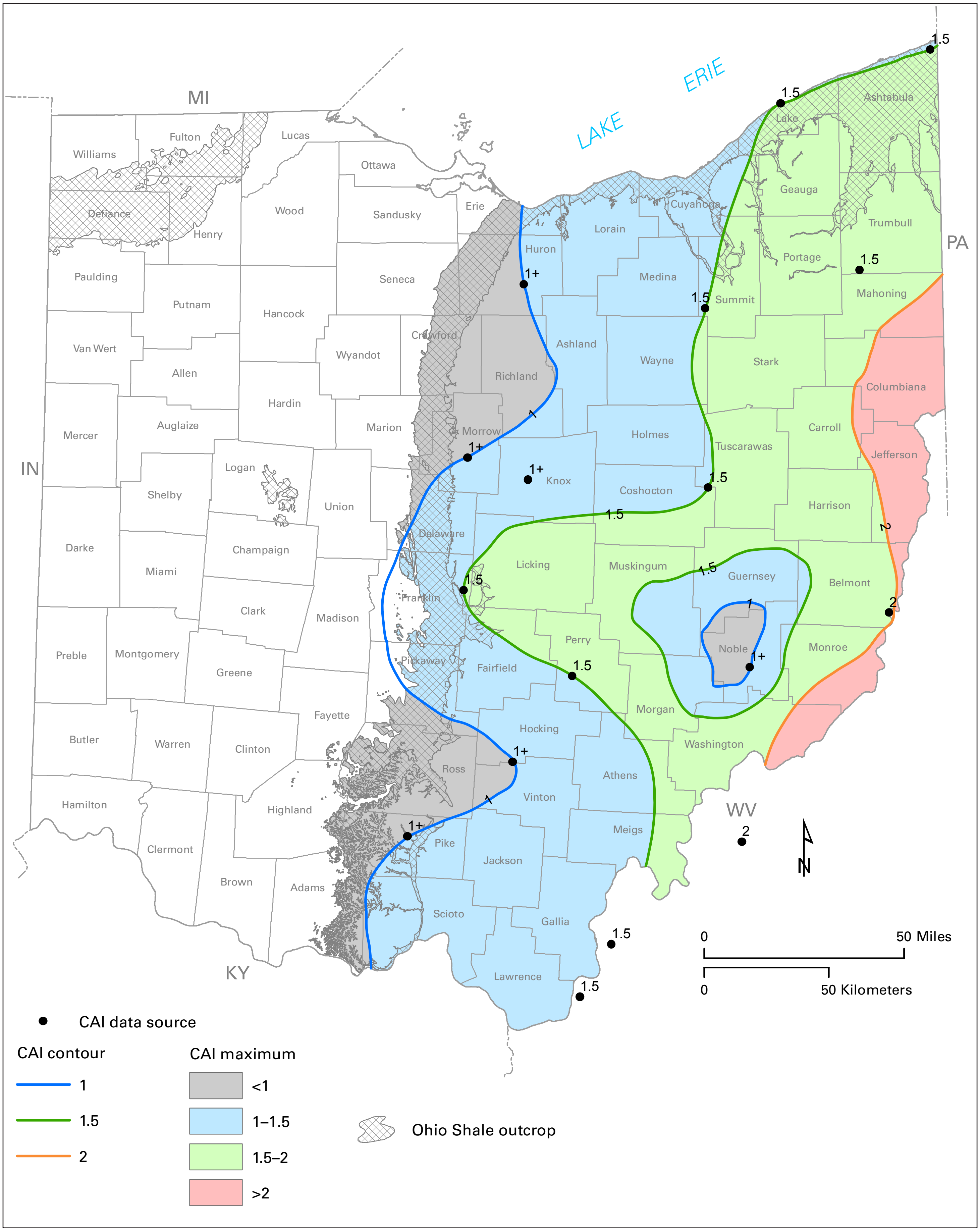

FIGURE 9. Isograd map of the conodont alteration index (CAI) for the Devonian shale interval in eastern Ohio.

comprehensive database from 201 wells in eastern and central Ohio. Preliminary maps of TOC, S_1, S_2, $\%R_o$, and CAI were constructed to better refine the source rock generative potential and thermal maturity of the Devonian shale interval in eastern Ohio.

Maximum TOC values per well for the Devonian shale interval range from 0.5 to 18.4 percent. A westward increase in TOC is present with over 70 percent of the wells having values greater than 4 percent (excellent source rock generative potential). Devonian shale maximum TOC values along the outcrop trend usually exceed 10 percent. The maximum TOC value of the Devonian shale interval is over twice that of the underlying Upper Ordovician Utica-Point Pleasant shale interval, which has a maximum value of 7.3 percent and values typically in the 2 to 3 percent range. The S_1 and S_2 values in the Devonian shale interval also indicate good source rock generative potential and maps display a westward increase similar to the TOC map. Maximum S_1 values per well range from 0.2 to 8.6 mg HC/g of rock. In eastern Ohio the S_1 values generally range from 1 to 2 mg HC/g of rock, which is indicative of good source rock generative potential. Maximum S_2 values are often in the 10–20 (very good) or 20–40 (excellent) mg HC/g rock range.

Vitrinite reflectance and CAI were mapped to assess the thermal maturity of the Devonian shale interval in eastern Ohio. A basinward (eastward) transition to more thermally mature rocks is evident on both maps. Maximum vitrinite reflectance values range from 0.33 to 1.34 $\%R_o$. A 0.6 $\%R_o$ isograd trends northeast–southwest through eastern Ohio and marks the onset of oil generation and separates the immature region to the west. The oil window transitions eastward to a condensate or wet gas window at values between 1.1 and 1.4 $\%R_o$ in extreme eastern Ohio. "Vitrinite suppression" is supported by previous USGS studies, comparison to $\%R_o$ in the overlying coals, and also with historic production numbers in southeastern Ohio, which indicate natural gas production with no liquids. Further study is recommended to account for the apparent "vitrinite suppression" and better refine the $\%R_o$ map. A limited dataset of 17 wells were used for the CAI map. The immature boundary trends approximately north–south in central Ohio based on CAI values of 1 or less. Onset of oil generation is generally considered to begin at a CAI of 1.0 and end at 2.0.

The preliminary maps and data generated for this report are a result of Ohio Geological Survey efforts to provide an updated compilation of information to assist explorationists in assessing this important and high potential oil-and-gas play. Thickness, depth, and pressure are additional geologic factors, as are current economic pricing conditions, which need to be taken into account in the assessment and exploration strategy of these organic-rich Devonian shale zones.

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APPENDIX

TABLE A-1. ***List of wells and data used for mapping source rock potential and thermal maturity in eastern Ohio.***

API NO.	PERM NO.	CORE #	CUTTING #	COUNTY NAME	SOURCE OF DATA	COMPANY NAME	MAX TOC (%)	MAX %R_o	MAX S_1 (mg HC/g of rock)	MAX S_2 (mg HC/g of rock)	MAX CAI
4701100537	537	NA	NA	Cabell	Repetski and others (2008)	Cyclops Corp.					1.5
4705100221	221	NA	NA	Marshall	Repetski and others (2008)	Allied Chemicals					2
4705300069	69	NA	NA	Mason	Repetski and others (2008)	United Fuel Gas					1.5
4710700756	756	NA	NA	Wood	Repetski and others (2008)	Exxon Co.					2
34001600130000	60013	2718		Adams	ODGS core records	N. American Exploration, Inc.	14.44				
34001600140000	60014	2719		Adams	ODGS core records	N. American Exploration, Inc.	13.71				
34005230410000	23041		3461	Ashland	ODGS core records	Deep Resources Llc	5.51	0.616	1.2	19.51	
34007200030000	20003		68	Ashtabula	ODGS core records	Magnolia Pet. Co.	4		0.61	13.05	
34007200150000	20015		440	Ashtabula	ODGS core records	Benedum - Trees Oil Co.	7.36		1.72	35.26	
34007200280000	20028		2008	Ashtabula	ODGS core records	Platco Corp.	7.08		1.79	33.96	
34007200960000	20096		846	Ashtabula	ODGS core records	Lenox Truck & Dozer	6.63		1.47	29.5	
34007200990000	20099		850	Ashtabula	ODGS core records	Northern Natural Gas Prod. Co.	6.15		1.98	22.05	
34007202130000	20213		2238	Ashtabula	Unpublished USGS data	Petrox, Inc.	1.28		0.81	2.51	
34007202660000	20266		2306	Ashtabula	ODGS core records	Dietrich Philip H.	7.29		2.58	32.12	
34007205240000	20524		2933	Ashtabula	Unpublished USGS data	Petrox, Inc.	1.47		0.66	3.34	
34007210870000	21087	2839		Ashtabula	ODGS core records	Bessemer & Lake Erie Rr	13.01	0.49			
34007210870000	21087	2839		Ashtabula	Repetski and others (2008)	Bessemer & Lake Erie Rr	7.89	0.59	2.98	28.76	1.5
34009217690000	21769		3095	Athens	ODGS core records	Premier Energy Corp.	3.54	0.72	1.37	16.43	
34009219160000	21916		3727	Athens	ODGS core records	Partners Oil Co.	3.64	0.64	2.48	33.11	
34009219630000	21963		3738	Athens	ODGS core records	Marshall Reba M.	3.69	0.7	2.43	13.61	
34009229690000	22969		4961	Athens	ODGS core records	Atha Edward E.	1.87	0.634	0.21	2.07	
34013201290000	20129		166	Belmont	ODGS core records	Texas Co.	8.73		3.09	10.87	
34013202770000	20277	2842		Belmont	Repetski and others (2008)	Columbia Gas Transmission	5.97	1.04	3.58	3.62	
34013202790000	20279		3473	Belmont	Unpublished USGS data	Ky. Crude Oil & Gas Co. Inc.	0.47		0.2	0.49	
34019208350000	20835	2845		Carroll	ODGS core records	Petrox, Inc.	6.33				
34029201520000	20152		227	Columbiana	ODGS core records	Dominion East Ohio	4.4		1.66	9.99	
34029206000000	20600		2279	Columbiana	ODGS core records	Pin Oak Petroleum Inc.	3.57		1.95	13.41	
34029206040000	20604		2247	Columbiana	ODGS core records	Tri-State Producing Co.	5.43		1.86	7.35	
34029206070000	20607		2246	Columbiana	ODGS core records	Pin Oak Petroleum Inc.	5.31		2.39	11.21	
34029206560000	20656		2411	Columbiana	ODGS core records	Statewide Oil & Gas Co.	4.45		2.76	9.59	
34031212740000	21274		795	Coshocton	ODGS core records	W.H. Bears	2.94		0.66	13.36	
34031220950000	22095		2790	Coshocton	ODGS core records	Samples, James F.	3.82		1.02	20.3	
34031221390000	22139		2953	Coshocton	Repetski and others (2008)	Columbia Gas Transmission	2.27	0.42	1.17	8.24	1.5
34031224600000	22460		3252	Coshocton	ODGS core records	Redman Oil Co.	7.42		2.54	36.51	
34031225700000	22570		3379	Coshocton	ODGS core records	Cyclops Corp.	3.39		1.26	15.89	
34031260030000	26003		3903	Coshocton	Unpublished USGS data	Rhdk Oil & Gas Llc/Dba Red Hil	3.59		1.98	14.94	
34033600410000	60041	2722		Crawford	ODGS core records	N. American Exploration, Inc.	11.38				
34033600420000	60042	2723		Crawford	ODGS core records	N. American Exploration, Inc.	11.19				
34033600440000	60044	2725		Crawford	ODGS core records	N. American Exploration, Inc.	11.34				
34033600450000	60045	2726		Crawford	ODGS core records	N. American Exploration, Inc.	12.11				
34033600460000	60046	2727		Crawford	ODGS core records	N. American Exploration, Inc.	12.53				
34033600470000	60047	2728		Crawford	ODGS core records	N. American Exploration, Inc.	11.86				
34033600480000	60048	2729		Crawford	ODGS core records	N. American Exploration, Inc.	11.31				
34033600490000	60049	2730		Crawford	ODGS core records	N. American Exploration, Inc.	11.54				
34033600500000	60050	2731		Crawford	ODGS core records	N. American Exploration, Inc.	10.48				
34033600510000	60051	2732		Crawford	ODGS core records	N. American Exploration, Inc.	11.72				
34035200570000	20057		60	Cuyahoga	ODGS core records	Benedum-Trees Co.	5.18		1.47	20.72	
34041600120000	60012	2648		Delaware	Repetski and others (2008)	Ohio Div. Of Geological Survey	8.82	0.35	1.96	41.7	
34041600130000	60013	2736		Delaware	ODGS core records	N. American Exploration, Inc.	11.85				
34041600140000	60014	2737		Delaware	ODGS core records	N. American Exploration, Inc.	11.6				
34043200050000	20005	734		Erie	Repetski and others (2008)	Nickel Plate Development Co.	5.8	0.45	1.44	25.85	
34045202340000	20234		636	Fairfield	Repetski and others (2008)	C. A. Davis Drg. Contractor	5.95	0.44	3.03	29.01	
34045617000000	61700	2740		Fairfield	ODGS core records	N. American Exploration, Inc.	13.83				
34045617000000	61700	2740		Fairfield	Repetski and others (2008)	Phillips Pet Co.	4.92	0.41	0.52	17.96	
34049600040000	60004	859		Franklin	Repetski and others (2008)	Andrix	7.32	0.44	2.04	36.31	1.5
34051600250000	60025	2744		Fulton	ODGS core records	N. American Exploration, Inc.	10.7				
34051600280000	60028	2747		Fulton	ODGS core records	N. American Exploration, Inc.	10.72				
34051600290000	60029	2748		Fulton	ODGS core records	N. American Exploration, Inc.	9.65				
34053204740000	20474	2874		Gallia	ODGS core records	Mitchell Energy Corp.	9.65	0.51			
34053204770000	20477	2871		Gallia	ODGS core records	Mitchell Energy Corp.	9.53	0.61			
34053204770000	20477	2871		Gallia	ODGS core records	Mitchell Energy Corp.	7.7	0.54	4.74	39.68	
34053204770000	20477	2871		Gallia	ODGS core records	Mitchell Energy Corp.	7.68	0.61	3.38	38.71	
34053204780000	20478	2875		Gallia	ODGS core records	Mitchell Energy Corp.	9.55	0.59			
34053204790000	20479	2872		Gallia	ODGS core records	Mitchell Energy Corp.	9.05	0.55			
34053204800000	20480		3557	Gallia	ODGS core records	Energy Search Inc.	4	0.72	1.37	18.93	
34053204820000	20482	2873		Gallia	ODGS core records	Mitchell Energy Corp.	11.79	0.64			
34053204820000	20482	2873		Gallia	Repetski and others (2008)	Mitchell Energy Corp.	2.49	0.47	0.46	7.59	
34053207690000	20769		3654	Gallia	ODGS core records	Elgin Service Center Inc.	3.92	0.78	1.64	20.02	
34053207690000	20769		3654	Gallia	Unpublished USGS data	Elgin Service Center Inc.	2.46		1.33	9.36	
34053209970000	20997	3695		Gallia	ODGS core records	Continental Resources Inc.	11.3	0.796	5.63	73.74	
34055200020000	20002		193	Geauga	ODGS core records	Benedum Trees Oil Co.	4.77		0.95	15.55	
34055200200000	20020		2392	Geauga	ODGS core records	Twm Petrolwum Inc.	7.11		1.14	19.13	
34059207990000	20799		7	Guernsey	Repetski and others (2008)	Well Supervision Inc.	2.92	0.45	0.69	7.47	
34059223890000	22389		3703	Guernsey	Unpublished USGS data	Kenoil	1.1		0.62	2.07	
34059226450000	22645		3763	Guernsey	ODGS core records	Eastland Energy Group Inc.	4.35	0.72	1.96	11.36	
34059227340000	22734		3868	Guernsey	Unpublished USGS data	Artex Oil Company	3.59		2.2	12.81	
34067201030000	20103		2287	Harrison	Unpublished USGS data	Moore Jerry Inc.	0.8		0.35	0.79	
34067201040000	20104		2389	Harrison	ODGS core records	Amerada Hess Corp.	2.85		1.05	6.08	
34067203450000	20345		3709	Harrison	ODGS core records	Sound Energy Co. Inc.		0.88			
34067203550000	20355		3735	Harrison	ODGS core records	Exco - North Coast Energy Inc.	3.62	1.28	2.22	5.25	
34069600740000	60074	2749		Henry	ODGS core records	N. American Exploration, Inc.	10.74				
34069600760000	60076	2751		Henry	ODGS core records	N. American Exploration, Inc.	10.95				
34069600780000	60078	2753		Henry	ODGS core records	N. American Exploration, Inc.	12.22				

API NO.	PERM NO.	CORE #	CUTTING #	COUNTY NAME	SOURCE OF DATA	COMPANY NAME	MAX TOC (%)	MAX %R_o	MAX S_1 (mg HC/g of rock)	MAX S_2 (mg HC/g of rock)	MAX CAI
34073204970000	20497		679	Hocking	Repetski and others (2008)	Barton A. Holl	5.22	0.39	2.51	25.91	
34073206110000	20611		738	Hocking	Repetski and others (2008)	Kewanee Oil Co.					1+
34075207290000	20729		662	Holmes	ODGS core records	Pan-Ohio Oil & Gas Co.	5.07		0.94	18.87	
34075214090000	21409		2412	Holmes	ODGS core records	Pin Oak Petroleum Inc.	7.73		2.25	44.4	
34075216090000	21609		2911	Holmes	ODGS core records	Raber, Aden B.	3.97		2.88	14.12	
34077200700000	20070		1980	Huron	Unpublished USGS data	Glynn Trolz & Assoc. Inc.	3.92		0.75	19.27	
34077201440000	20144	2823		Huron	Repetski and others (2008)	D. L. Woody Inc.					1+
34077600240000	60024	2757		Huron	ODGS core records	N. American Exploration, Inc.	10.3				
34079201020000	20102		3465	Jackson	ODGS core records	Artex Oil Company	8.19	0.72	2.17	44.34	
34079201680000	20168	NA	NA	Jackson	ODGS core records	Cgas Exploration	8	0.51	8.06	41.98	
34081203400000	20340		1060	Jefferson	ODGS core records	Lake Shore Pipeline Co.	4.3		1.98	4.25	
34081204120000	20412		3747	Jefferson	ODGS core records	Exco - North Coast Energy Inc.	3.35	1.34	1.55	2.88	
34081204120000	20412		3747	Jefferson	Unpublished USGS data	Exco - North Coast Energy Inc.	0.87		0.33	0.7	
34083225990000	22599	2900		Knox	ODGS core records	Maram Energy Co.	7.63	0.76			
34083225990000	22599	2900		Knox	Repetski and others (2008)	Maram Energy Co.	7.2	0.63	4.74	39.13	1+
34085200170000	20017	855		Lake	Repetski and others (2008)	Morton Salt Co.	6.67	0.46	4.61	31.7	1.5
34085201420000	20142		2509	Lake	Unpublished USGS data	Ici Americas Inc.	2.7		1.33	8.86	
34085202210000	20221		3453	Lake	ODGS core records	Lubrizol Corp.	1.47				
34087202570000	20257		3609	Lawrence	Unpublished USGS data	Petro Quest Inc.	2.29		1	7.27	
34087202580000	20258		3721	Lawrence	ODGS core records	Petro Quest Inc.	4.93	0.69	2.62	24.16	
34089233410000	23341		3755	Licking	ODGS core records	Brown Phillip H. Jr. Corporation	8.79	0.67	2.82	31.52	
34089234990000	23499		3707	Licking	ODGS core records	Enervest Operating Llc.	6.64	0.59	3.31	20.74	
34093211000000	21100	2909		Lorain	ODGS core records	Columbia Gas Transmission	11.66	0.75			
34093211000000	21100	2909		Lorain	Repetski and others (2008)	Columbia Gas Transmission	5.66	0.36	2.74	24.14	
34093605050000	60505	2762		Lorain	ODGS core records	N. American Exploration, Inc.	8.56				
34093605060000	60506	2763		Lorain	ODGS core records	N. American Exploration, Inc.	8.46				
34099200200000	20020		63	Mahoning	ODGS core records	Magnolia Petroleum	4.43		1.09	9.87	
34099201790000	20179		1016	Mahoning	ODGS core records	Bocor Holdings, Llc/Bocor Prod.	3.73		1.43	13.83	
34099211890000	21189		3748	Mahoning	Unpublished USGS data	H & W Energy	2.68		0.97	8.23	
34101600290000	60029	2766		Marion	ODGS core records	N. American Exploration, Inc.	11.09				
34101600310000	60031	2768		Marion	ODGS core records	N. American Exploration, Inc.	14.01				
34103211430000	21143		819	Medina	Unpublished USGS data	Bocor Holdings, Llc/Bocor Prod.	3		1.51	8.46	
34105213130000	21313		827	Meigs	ODGS core records	The Ohio Fuel Gas Co.	4.94	0.79	1.77	18.15	
34105214220000	21422		2249	Meigs	ODGS core records	Jadoil Inc. D. Vernau	1.48				
34105220580000	22058	2921		Meigs	ODGS core records	Columbia Gas Transmission	6.34	0.78	3.95	27.28	
34105220580000	22058	2921		Meigs	ODGS core records	Columbia Gas Transmission	2.88	0.59	0.35	11.15	
34105220580000	22058	2921		Meigs	ODGS core records	Columbia Gas Transmission	5.7	0.73			
34105220580000	22058	2921		Meigs	Repetski and others (2008)	Columbia Gas Transmission	5.52	0.48	4.34	21.68	
34105224990000	22499	2922		Meigs	Unpublished USGS data	Columbia Gas Transmission	0.57		0.97	0.84	
34111203450000	20345	NA	NA	Monroe	ODGS core records	Miley Gas Company	2.21		1.33	5.51	
34111218810000	21881		3714	Monroe	ODGS core records	Buckeye Oil Producing Co.	1.53	0.82	0.44	1.33	
34115217720000	21772		3731	Morgan	ODGS core records	Inland Drilling Co Inc.	4.05	0.62	2.14	14.85	
34115217720000	21772		3731	Morgan	Unpublished USGS data	Inland Drilling Co Inc.	2.39		1.07	6.06	
34115235700000	23570		3848	Morgan	Unpublished USGS data	Hanna M. A. Co.	1.25		0.64	2.59	
34115237590000	23759		4964	Morgan	ODGS core records	Smith Ronald Dba Chipco	1.64		0.37	2.82	
34117600380000	60038	2769		Morrow	ODGS core records	N. American Exploration, Inc.	12.81				
34117600390000	60039	2770		Morrow	ODGS core records	N. American Exploration, Inc.	12.11				
34117600390000	60037	2770		Morrow	Repetski and others (2008)	Phillips Pet Co.	9.92	0.43	4.41	55.69	1+
34117600410000	60041	2772		Morrow	ODGS core records	N. American Exploration, Inc.	13.18				
34117600420000	60042	2773		Morrow	ODGS core records	N. American Exploration, Inc.	14.25				
34117600430000	60043	2775		Morrow	ODGS core records	N. American Exploration, Inc.	12.42				
34117600440000	60044	2776		Morrow	ODGS core records	N. American Exploration, Inc.	12.35				
34117600450000	60045	2777		Morrow	ODGS core records	N. American Exploration, Inc.	14.37				
34117600460000	60046	2778		Morrow	ODGS core records	N. American Exploration, Inc.	10.81				
34117600480000	60048	2780		Morrow	ODGS core records	N. American Exploration, Inc.	13.33				
34117600540000	60054	2786		Morrow	ODGS core records	N. American Exploration, Inc.	11.18				
34117600550000	60055	2787		Morrow	ODGS core records	N. American Exploration, Inc.	10.47				
34119201460000	20146		65	Muskingum	ODGS core records	E. M. Shields	4.42		0.53	11.56	
34119216170000	21617		799	Muskingum	Repetski and others (2008)	Barco Corporation	4.02	0.43	2.18	18.4	
34119219500000	21950		2128	Muskingum	ODGS core records	Sidwell, Cris D.	3.68		0.96	20.85	
34119252500000	25250		3767	Muskingum	ODGS core records	Cgas Exploration	5.64	0.55	2.34	20.41	
34119252500000	25250		3767	Muskingum	Unpublished USGS data	Cgas Exploration	3.64		1.3	18.05	
34121206580000	20658		385	Noble	ODGS core records	H. Rey. Halvenston	9		2.36	11.79	
34121213120000	21312		2292	Noble	ODGS core records	Waite, James D.	3.02		0.79	5.57	
34121221000000	22100		3723	Noble	Unpublished USGS data	Zilkha Energy Inc.	1.24		0.42	1.6	
34121221130000	22113		3734	Noble	ODGS core records	Green Gas Co	3.64	0.98	2.21	9.27	
34121222550000	22255	2936		Noble	ODGS core records	Stonebridge Operating Co.	12.63	1.16	6.51	28.65	
34121222550000	22255	2936		Noble	ODGS core records	Stonebridge Operating Co.	11.35				
34121222550000	22255	2936		Noble	Repetski and others (2008)	Stonebridge Operating Co.	7.03	1.01	4.5	17.72	1+
34127223800000	22380		1573	Perry	Repetski and others (2008)	Kentucky Drilling & Operating Corp.	4.56	0.46	2.21	22.34	
34127228550000	22855		2290	Perry	Repetski and others (2008)	Kentucky Drlg. & Operating Corp.					1.5
34129600030000	60003	2788		Pickaway	ODGS core records	N. American Exploration, Inc.	11.38				
34129600030000	60003	2788		Pickaway	Repetski and others (2008)	Phillips Pet Co.	10.54	0.42	2.05	43.56	
34129600050000	60005	2790		Pickaway	ODGS core records	N. American Exploration, Inc.	8.86				
34129600060000	60006	2791		Pickaway	ODGS core records	N. American Exploration, Inc.	10.92				
34129600070000	60007	2792		Pickaway	ODGS core records	N. American Exploration, Inc.	13.88				
34129600080000	60008	2794		Pickaway	ODGS core records	N. American Exploration, Inc.	9.95				
34129600090000	60009	2796		Pickaway	ODGS core records	N. American Exploration, Inc.	12.08				
34129600100000	60010	2797		Pickaway	ODGS core records	N. American Exploration, Inc.	12.06				
34129600110000	60011	2799		Pickaway	ODGS core records	N. American Exploration, Inc.	10.87				
34129600120000	60012	2800		Pickaway	ODGS core records	N. American Exploration, Inc.	11.21				
34129600130000	60013	2801		Pickaway	ODGS core records	N. American Exploration, Inc.	10.63				
34129600140000	60014	2802		Pickaway	ODGS core records	N. American Exploration, Inc.	10.8				

API NO.	PERM NO.	CORE #	CUTTING #	COUNTY NAME	SOURCE OF DATA	COMPANY NAME	MAX TOC (%)	MAX %R_O	MAX S_1 (mg HC/g of rock)	MAX S_2 (mg HC/g of rock)	MAX CAI
34131200220000	20022	2946		Pike	Repetski and others (2008)	Karl Wehmeyer & Co.					1+
34131600600000	60060	2803		Pike	ODGS core records	N. American Exploration, Inc.	18.26				
34131600610000	60061	2804		Pike	ODGS core records	N. American Exploration, Inc.	12.62				
34131600610000	60061	2804		Pike	Repetski and others (2008)	Phillips Pet Co.	7.2	0.42	1.71	34.4	
34131600620000	60062	2805		Pike	ODGS core records	N. American Exploration, Inc.	13.3				
34131600630000	60063	2806		Pike	ODGS core records	N. American Exploration, Inc.	13.77				
34133200020000	20002		242	Portage	ODGS core records	J. W. Cashdollar	5.37		1.96	20.74	
34133205180000	20518		3092	Portage	ODGS core records	Enervest Operating Llc.	5.19		2.37	21.22	
34139205230000	20523	2949		Richland	Repetski and others (2008)	Fry, Andrew M.	7.27	0.43	1.94	33.39	
34139205270000	20527	2955		Richland	Repetski and others (2008)	Bates, Lew Jr.	8.08	0.43	5.23	41.17	
34141600060000	60006	562		Ross	Repetski and others (2008)	OSU Engineering	4.43	0.4	1.2	20.96	
34141600250000	60025	2807		Ross	ODGS core records	N. American Exploration, Inc.	14.23				
34141600260000	60026	2808		Ross	ODGS core records	N. American Exploration, Inc.	13.57				
34145201930000	20193	2959		Scioto	ODGS core records	Continental Oil Co.	8.28	0.57	1.98	29.31	
34145202120000	20212	2161		Scioto	ODGS core records	Aristech Chemical Corp.	6.07	0.7	1.81	30.38	
34145601410000	60141	3409		Scioto	Unpublished USGS data	Aristech Chemical Corp.	8.64		4.93	55.89	
34145601450000	60145	2813		Scioto	ODGS core records	N. American Exploration, Inc.	21.08				
34145601460000	60146	2814		Scioto	ODGS core records	N. American Exploration, Inc.	16.58				
34145601460000	60146	2814		Scioto	Repetski and others (2008)	Phillips Pet Co.	9.57	0.33	4.03	51.04	
34145601470000	60147	2815		Scioto	ODGS core records	N. American Exploration, Inc.	13.55				
34145601490000	60149	2816		Scioto	ODGS core records	N. American Exploration, Inc.	14.15				
34145601530000	60153	2817		Scioto	ODGS core records	N. American Exploration, Inc.	13.46				
34145601540000	60154	2818		Scioto	ODGS core records	N. American Exploration, Inc.	14.41				
34151228270000	22827		3704	Stark	Unpublished USGS data	Miller, William S. Inc.	1.9		0.79	5.03	
34153604170000	60417	510		Summit	Repetski and others (2008)	Pittsburgh Plate Glass Co. Columbia Chem. Div.	9.21	0.48	4.76	39.42	1.5
34155212380000	21238	2962		Trumbull	Repetski and others (2008)	Columbia Gas Transmission	8.44	0.42	5.67	37.02	1.5
34157200040000	20004		41	Tuscarawas	ODGS core records	O. F. G.	3.6		1.15	10.34	
34157200660000	20066		209	Tuscarawas	Repetski and others (2008)	Brendel Prod. Co.	2.58	0.44	0.85	8.93	
34157201010000	20101		308	Tuscarawas	ODGS core records	Columbian Carbon Co.	1.77		0.43	6.56	
34157207880000	20788		820	Tuscarawas	ODGS core records	Dr. Thos. Christopher	5.33		1.65	15.88	
34157210360000	21036		2071	Tuscarawas	ODGS core records	Eclipse Resources-Ohio Llc.	2.57		0.8	7.48	
34157211610000	21161		2337	Tuscarawas	ODGS core records	Tipka Energy Devlopment Co.	2.42		1.11	8.87	
34157216610000	21661		2810	Tuscarawas	ODGS core records	Welling John	3.44		1.14	12.27	
34157233200000	23320		3733	Tuscarawas	Unpublished USGS data	Enervest Operating Llc.	1.13		0.37	2.11	
34163203310000	20331		2015	Vinton	ODGS core records	Doyle Baird	5.32		1.32	26.1	
34163203690000	20369		2508	Vinton	ODGS core records	Quaker State Oil Ref Corp.	6.93	0.62	1.81	30.04	
34163205570000	20557	NA	NA	Vinton	ODGS core records	Donald Byers Oil & Gas Llc.	9.92	0.48	4.45	67.91	
34163206190000	20619	NA	NA	Vinton	ODGS core records	Donald Byers Oil & Gas Llc.	12.65	0.46	5.9	65.26	
34163206540000	20654	NA	NA	Vinton	ODGS core records	Trainer, Everett C.	18.37	0.49	7.35	115.04	
34167203030000	20303		481	Washington	ODGS core records	Columbian Carbon Co. & Joe Rubin	4.7		1.66	9.28	
34167215150000	21515		506	Washington	ODGS core records	Ohio Fuel Gas Co.	6.08		2.02	12.09	
34167216980000	21698		2734	Washington	ODGS core records	B.H. Putnam	2.39		1.12	5.91	
34167217000000	21700		2732	Washington	ODGS core records	B.H. Putnam	5.98		2.39	13.56	
34167231000000	23100		2382	Washington	ODGS core records	Amerada Petroleum Corp.	3.55		0.81	4.08	
34167233060000	23306		2500	Washington	ODGS core records	Whipple Run Oil & Gas Co.	2.54		1.38	4.3	
34167235210000	23521	2966		Washington	ODGS core records	Indian Hills Resources Llc.	4.85	0.868	3.05	14.56	
34167235210000	23521	2966		Washington	ODGS core records	Indian Hills Resources Llc.	2.71	0.77	2.2	6.75	
34167235210000	23521	2966		Washington	Repetski and others (2008)	Indian Hills Resources Llc.	2.93	0.92	2.44	11.09	
34167252410000	25241		3760	Washington	ODGS core records	Triad Hunter Llc.	3.86	1.06	2.32	5.79	
34169215640000	21564		2252	Wayne	ODGS core records	Wenner Petroleum Corp.	1.66		0.33	3.7	

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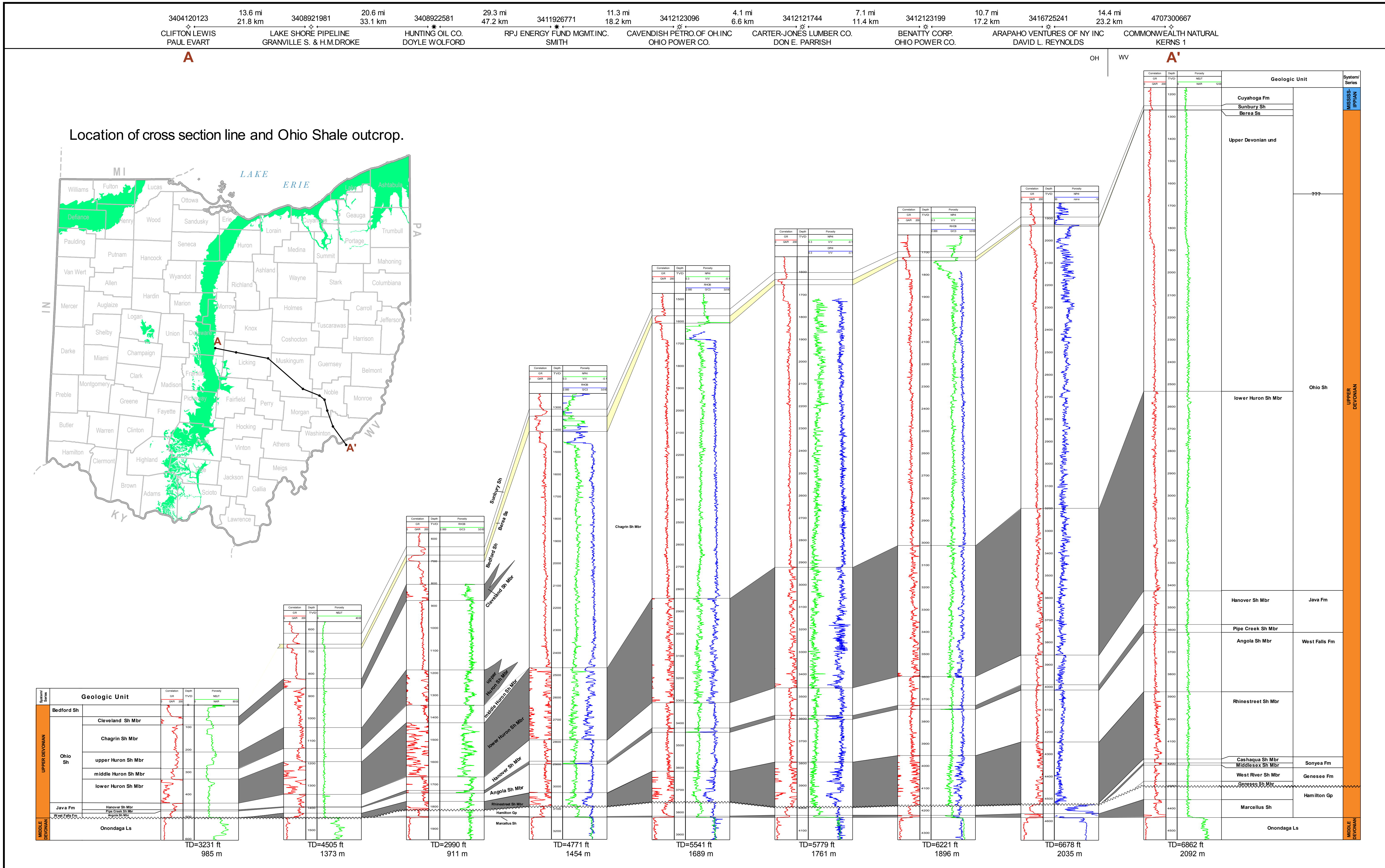

Unit abbreviations: Fm = Formation, Gp = Group, Ls = Limestone, Mbr = Member, Sh = Shale, Ss = Sandstone, und= undifferentiated.

PLATE 1. Regional stratigraphic cross section illustrating the Middle and Upper Devonian interval from Delaware County, Ohio, to Pleasants County, West Virginia.